Deep Ground Penetrating Radar (GPR) WIPD-D Models of Buried Sub-Surface Radiators

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Abstract: — The proliferation of strategic subsurface sanctuaries has increased the need for enhanced remote sensing techniques providing for the accurate detection and identification of deeply buried objects. A new Ground Penetrating Radar (GPR) concept is proposed in this paper to use subsurface radiators, delivered as earth penetrating non-explosive, electronic "e-bombs", as the source of strong radiated transmissions for GPR experiments using ground contact or airborne receivers. Three-dimensional imaging techniques for deeply buried targets are being developed based on two-dimensional synthetic aperture radar (SAR) data collection techniques. Experiments over deep mine shafts have been performed to validate the 2D SAR processing algorithms. WIPL-D models have been used to verify the significant enhancement in the received signal-to-noise ratio obtained by burying the transmitter under the surface of the earth. Simple ray-tracing techniques have also been used to confirm the enhancements.

Keywords: Deep Ground Penetrating Radar, Subsurface radiators, buried objects, SAR, GPR, RCS

1. Introduction

In this paper, trade-offs associated with critical issues involved with GPR techniques are addressed. The proliferation of subsurface structures used as command posts and storage sites for conventional or nuclear weapons has increased the need for remote sensing technologies providing for the accurate detection and identification of deeply buried objects. HF radiation is required for deep penetration. Remote sensing using an elevated GPR system, which provides a safe stand-off distance, reduces the surface penetration of the transmitted wave and radar resolution. Ground foliage and the mismatch at the earth/air interface further reduce the transmitted energy available in the wave propagating in the earth. Therefore, a new concept is proposed to use a subsurface radiator, delivered as an earth penetrating non-explosive, electronic bomb (e-bomb), for the source of the transmission and ground contact or airborne receivers. The goal is to achieve improved subsurface surveillance of buried objects, target detection and identification, wide-area surveillance, targeting, battle damage assessment, and buried facility parameters (lateral location, depth, size, shape, and portals). This technique will improve the detection process of locating deeply buried objects. Three-dimensional imaging techniques for deeply buried targets are developed based on two-dimensional SAR data collection techniques. Near-field focusing is performed digitally to combine the 2D data collected over a planar grid of equally-spaced sample points to form a 3D image of subsurface features**.**

2. Ground Penetration Radar (GPR)

Commercially viable GPR typically fall into two categories, shallow penetrating systems operating to depths of five feet or less and very deep penetrating systems operating to depth of hundreds or even thousands of feet. Numerous manufacturers produce both impulse and spread spectrum shallow penetrating radars [1] designed to look for pipes or similar objects near the surface, and literature is widely available on the internet, while a limited number of very deep penetrating radars have been built. These very deep penetrating radar

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 JAN 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Deep Ground Penetrating Radar (GPR) WIPD-D Models of Buried Sub-Surface Radiators**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Air Force Academy Colorado Springs CO 80840, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001846, Applied Computational Electromagnetics Society 2005 Journal, Newsletter, and Conference., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

systems, custom built for oil and gas exploration, operate below the AM broadcast band. Due to antenna constraints, they operate with tuned antennas [2] and large time-bandwidth products, so that the transmitting antenna can be continuously tuned to each new frequency component as the frequency synthesizer steps or sweeps through the band. This paper addresses a third, even more difficult category of GPR, one designed to operate to depths of several hundred feet, yet with operational constraints that demand rapid mobility, preferably mounted on an airborne platform, and without the long "stationary" dwell at each location that would permit use of tunable antennas. Here, a combination of airborne sensors operating in conjunction with a buried or subsurface radiator offers the only practical solution to a very difficult design problem. This new configuration is modeled with WIPL-D to determine the benefits of burying the transmitting antenna.

3. Sub-Surface Radiators

Earth penetrating munitions, such as the laser guided GBU-28 "Bunker Buster", emerged in the early 1990s. Sled tests verified that the bomb could penetrate over 20' of concrete, while earlier flight tests proved that the bomb could penetrate more than 100' of earth. About the same time, the "smart bomb" or the e-bomb became available. Then, came the advent of the earth penetrating radiator, that is, the underground e-bomb, which can penetrate the earth without blowing up prematurely or destroying itself on impact.

It is proposed to replace the "explosives" in the e-bomb with "electronics" to produce an underground earth penetrating non-explosive, electronic radiator. This earth penetrating e-bomb can provide a subsurface transmitter (radiating source) for GPR experiments used with ground contract or airborne receivers. One important application is to surface contact synthetic aperture radar (SAR).

Of practical concern when operating with a buried radiator, is the issue of data communications. Here, the problem of data transmission to the war fighter is compounded by the effects of propagation attenuation in the ground, and air-earth mismatch losses. A low-cost, light-weight transponder is being developed.

Alternately, for extended battery life, the transmitter can be above-ground, and the receiver below-ground. In addition, due to the attenuation of signals by the earth, there is less interference with a sensitive buried receiver from intentional/unintentional sources of radiation. Also, the intrinsic wavelength of the radiated waves in the lossy earth is smaller than that in the air. Therefore, the subsurface antenna can be smaller than one in the air.

The advantages of a subsurface radiator over the conventional above-ground radiator include the elimination of the "ground bounce", the large reflection off the mismatch from the earth/air interface and ground foliage, and refraction into the earth, reduced beam distortion (ground focusing/defocusing), dissipation and signal attenuation, signal distortion, etc. resulting in significantly more power delivered into the ground, improved signal-to-noise ratio (SNR), better control over the radiated beam from the antenna, and simple performance predictions.

4. Embedded Scenerio

Typical e-bomb operations are shown Figures 1-2.

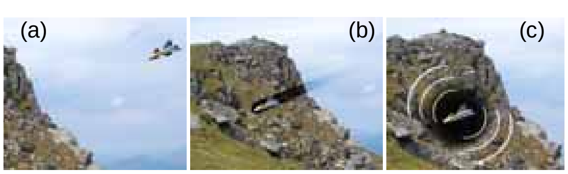

Figure 1: Incoming/penetrating/transmitting e-bomb missile

Figure 2: Ground embedded e-bomb operating in close proximity to potential threat target subsurface facility.

a) Radiation Efficiency: An improvement in radiation efficiency is expected due to the shorter wavelength and increased apparent length of the subsurface radiator compared to an above-ground antenna. This effect varies with the square root of the dielectric constant, which for a relative dielectric constant of $_r$ = 16, would shorten the wavelength by a factor of 4. Since the size of the radiator is limited in practice, an expected improvement in radiation efficiency from 20% with the above-ground antenna to 80% with the subsurface radiator could typically result.

b) Loss Through Ground: The subsurface radiator is deployed in close proximity to the target of interest. Thus, the propagation loss through the earth medium will be reduced compared to a radiator positioned on the surface. In a typical case, where the propagation loss through the ground is 0.25dB/ft, and the surface antenna is 100 ft from the target, while the subsurface radiator is located 40 ft away, we would expect a 15dB improvement in favor of the subsurface radiator.

c) Air-Earth Interface: A loss is typically incurred when incident radiation penetrates the ground from the air, due to the mismatch in dielectric constant and conductivity. An improvement of approximately 3dB is expected for the subsurface radiator by elimination of this loss effect.

d) Antenna Lobing: Lobes in the radiation pattern of an antenna sited on the surface of the ground have been observed and documented. These lobes can favor or attenuate the returns from desired targets by up to +/-10dB, depending on their location and the geometry of the bistatic path from transmitter to target, and to the receiver. Much less (if any) such variability is expected for the subsurface radiator.

e) Performance Summary

Surface	Subsurface	Radiator	Improvement
Radiation Efficiency	20%	80%	6 dB
Ground Losses	25dB	10 dB	15 dB
Air Earth Interface	-3dB	0dB	3 dB
Antenna Lobing	+/- 10 dB	0 dB	+/- 10 dB
TOTAL IMPROVEMENT			14 – 34 dB

5. Critical Issues: Clutter/Mismatch

Two critical issues are addressed with the application of the subsurface e-bomb transmitter. First and foremost is the additional energy on target achieved due to the elimination of the air-earth mismatch loss. Of equal importance is the significant reduction in surface clutter backscatter to the airborne receiver platform. As such, not only is the signal-to-thermal-noise enhanced, but so is the signal-to-clutter.

6. Critical Physical Phenomena

Point electromagnetic sources at long distances provide for a nearly planar radiation wave front, which is ideal for wide area surveillance radar under a variety of conditions. This is especially true for the detection and tracking of airborne threat targets from airborne radars. In ground penetrating radar, we attempt to place the transmitter and/or receiver as close to the target area as possible. This is due to range equation power limitations. With such close proximity to the subsurface target of interest, we violate the plane wave assumption and compound the signal processing requirements. A confluence of factors compound the problems associated with the operation of ground penetrating radars for the detection of hardened and deeply buried targets, and our ability to automatically discern returns from natural structures and subsurface targets. Most obvious among these factors is the dielectric mismatch loss at the air-earth interface. As such, the energy on target is significantly reduced.

Snell's Law and Fresnel's Law may be used to describe the transmitted and reflected energy at the air-earth interface. Two significant physical phenomena occur here. First, the relative dielectric constant of the earth ε_{re} (dry earth being 4 or greater, with 15 typical for moist soil) and the angle of incidence determines the bending of the rays of incident energy upon transversing the interface, while the ratio of the energy transmitted to reflected is $4/\left(1-\sqrt{1/\varepsilon_{re}}\right)^2$ for non-magnetic materials. Furthermore, the plane wave impinging upon the air-earth interface is distorted to be co-sinusoidal with respect to the normal.

An additional problem arises due to the fact that surface reflections from strong scatterers such as buildings, automobiles, and trucks will cohere and mask subsurface returns. Furthermore, receiver dynamic range is ultimately limited by these scattered returns from surface clutter. Direct path leakage between the transmitter and receiver may easily be mitigated via classical side-lobe cancellation, which offers in excess of 20dB in interference reduction. Ultimately, surface clutter reflections remain and ultimately mask weak target returns or even cause receiver saturations. Beyond that, the radar range equation is dramatically altered to include a dielectric constant propagation attenuation factor in addition to R^4 range attenuation. This attenuation is exponential and measured in dB per unit depth. For moderate depths of penetration, the dielectric constant propagation attenuation factor could be orders of magnitude greater than the R^4 range attenuation. In numerous ground penetrating radars, surface contact antennas are employed to increase energy coupling into the ground. To further improve performance, these antennas would have to be buried.

Figure 3 presents a pictorial view of experiments conducted at Gouvernour, NY. Two bowtie antennas are used to collect data over a grid containing 121 points on the surface. The transmitter remained stationary while the receiver was moved to cover 121 equally spaced points on the ground. A manmade drift (mine) 150-160 feet below the surface was detected and imaged using an experimental setup described by Lynch [4] and Brown [5], as shown in Figure 3. Most notable is the extensive unfocused clutter spanning from 20 to 40 feet below the ground. Using a subsurface e-bomb transmitter, the unfocused clutter at or near the air-earth interface would be significant reduced. Burying the transmit antenna is not always practical, especially in a warfare environment.

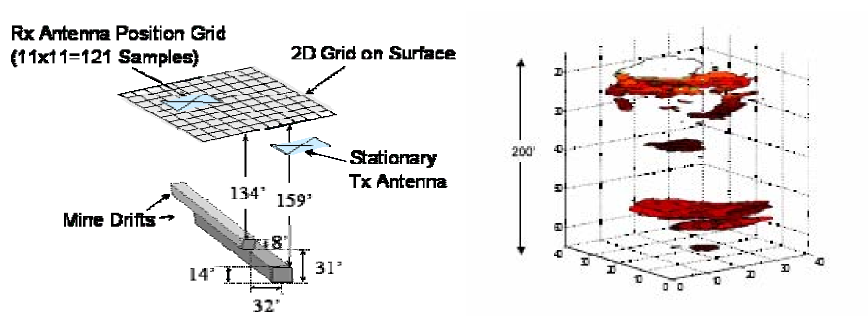

Figure 3: Early work on deep penetrating radar utilized surface contact antennas operating bistatically to detect natural and manmade objects to a depth of 200 feet.

A simple scenario has airborne sensors operating to detect likely hardened and deeply buried targets. Then, a subsurface radiator missile is launched, buries itself in the ground between 20 and 100 feet, and begins to radiate. This is illustrated in Figure 4. Here, we have a combination elevated/airborne transmitter/receiver pair operating in conjunction with a subsurface transmitter for precision engagement. In figure 5, a long term goal includes airborne UAV based transmitter and receiver pairs. This may be impractical given the difficult environments in which subsurface facilities may be built.

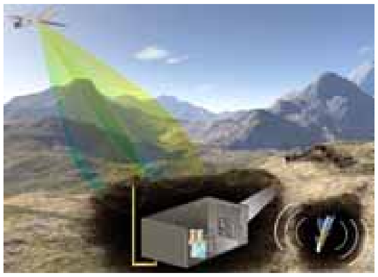

Figure 4: Realistic scene with an elevated (aerostat) airborne receiver, and a subsurface radiator to facilitate precision engagement.

Figure 5: UAV based bistatic GPR for subsurface facility detection.

Other missiles containing receiver equipment could be launched into the ground, but a more realistic scenario uses the existing airborne sensors to collect and analyze radar data. The goal is to facilitate precision engagement of the hardened and deeply buried targets with bunker buster weapons, or similar munitions. The need for a target image or signal strength estimates becomes secondary.

The goal of imaging a hardened and deeply buried facility is intended to please the human operator. What is ultimately needed is automatic target detection and declaration, which is more in line with the emerging concepts of operations using UAVs and UGVs. As such, freedom to select transmit and receive geometries favorable to the binary hypothesis “target present / target absent” is desired. Imaging for discrimination is secondary to this goal, and only used when marginal test statistics are available from the analysis of measurement data.

7. Modeling & Simulation

Comparisons have been made between underground and above ground transmitters. The target model incorporates both specular and diffuse scattering phenomena along with path attenuation. The composite reflection incorporates specular/diffuse scatterers within an anisotropic scenario [6]. A perfectly conducting target was examined according to the target, transmitter and receiver geometry as shown in Figure 6.

A simple WIPL-D model was constructed of dielectric blocks to model the tunnel below a homogeneous erath, as shown in Figure 7 (solid) and 8 (grid). The transmitting antenna was located 6” above or 2 ft below the ground. The receiving antenna was located 3” below the ceiling of the tunnel. The received energy when the transmitter was located below the ground was compared to the received energy when the transmitter was located above the ground. The enhancement predicted by WIPL-D was 15.1 dB; the enhancement predicted by the ray-tracing algorithm was 15.8 dB. This is a significant increase in received power, which translates into stronger signals at greater depths.

The first experiment (see Figure 7) placed the transmitter 6” above the ground and measured the returns at each receiver position in the receiving grid. The second experiment (see Figure 8) placed the transmitter 6” below the ground and measured the returns at the same receiver positions.

All outputs are in terms of integrated power at each receiver location. The simulator does not incorporate the three-dimensional image generation and does not include direct path, however direct path can be evaluated within the simulator. Direct path clutter can be considerably reduced through the use of a high-pass filter within the three-dimensional imaging routine.

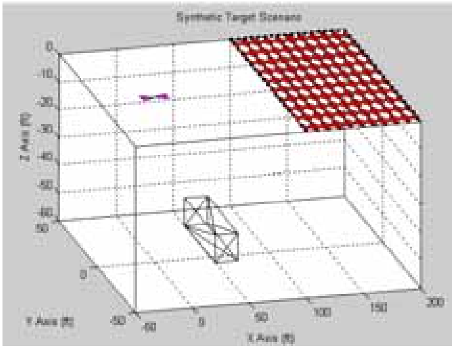

Figure 6. SAR Geometry

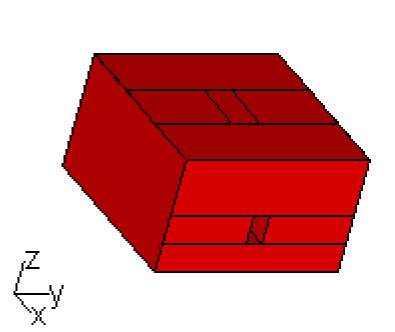

Figure 7. WILP-D Solid Model

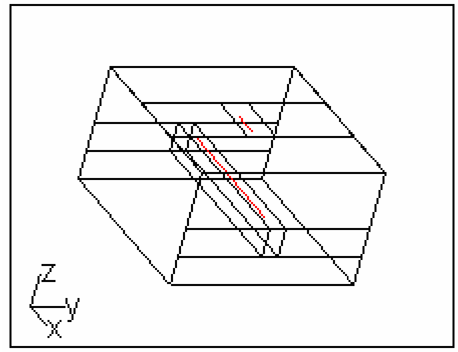

Figure 8. WIPL-D Grid Model (Transmitting Antenna Above or Below Ground).

8. Conclusions

These results indicate that by embedding the transmitter only 6” into the ground the received power is increased by more than 16 dB.

Additional concerns with e-bomb surface penetrating radiators arise. Most notable among these is the transmission of receiver data to the user. An unattended ground station (UGS) attached to the e-bomb via fiber optic is easily deployed upon surface impact. This UGS relays subsurface receiver data directly to the UAV borne transmitter platform for use in image formation and solves the data communications problem. The ability to perform subsurface imaging to depths of 200’ have already been demonstrated by Brown in [3] and presented in Figure 3 above. Furthermore, reference [3] presents below ground images using thinned arrays with data collected in patterns characteristic of loitering UAV platforms.

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